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Air Force Research Laboratory

Integrity ★ Service ★ Excellence

Time-Resolved Emission Spectroscopy of Field Reversed Configuration Thruster

August 31st, 2016

Gary Z. Li
In-Space Propulsion Branch (RQRS)
Aerospace Systems Directorate
Edwards AFB, CA

Outline

- About Me
- Objective
- Introduction
- Experimental Setup
- Data Processing
- Results
- Conclusions

About Me

- 3rd year Ph.D. candidate in Aerospace Eng. at UCLA
- B.A. in Astrophysics and Physics from UC Berkeley
  - Senior thesis on detection of faint supernovae in ultra-luminous infrared galaxies (ULIRGs)

Objective

To study the formation mechanisms of an FRC thruster using time-resolved optical emission spectroscopy.

Introduction

- **Field Reversed Configuration (FRC) thrusters are candidates for next generation high-powered electric propulsion (EP)**
- **Advantages over competing technologies in same power range (*Hall thrusters, MPDs, VASIMR*)[1]**

[1] Brown, D., Beal, B., Haas, J. (2010) AFRL High Power Electric Propulsion Technology Development

Introduction

- **Field Reversed Configuration (FRC) thrusters are candidates for next generation high-powered electric propulsion (EP)**
- **Advantages over competing technologies in same power range (*Hall thrusters, MPDs, VASIMR*)[1]**
  - **Throttleable → momentum transfer control**
  - **Electrodeless → near zero erosion**
  - **Low specific mass → less thruster, more payload**
  - **Alternative propellants → green (AF-M315), ISRU (Martian air)**
  - **Higher overall efficiency* → more bang for your buck**

**projected*

[1] Brown, D., Beal, B., Haas, J. (2010) AFRL High Power Electric Propulsion Technology Development

Introduction

- Field Reversed Configuration (FRC) thrusters are candidates for next generation high-powered electric propulsion (EP)
- Advantages over competing technologies in same power range (*Hall thrusters, MPDs, VASIMR*)[1]
  - Throttleable → control momentum transfer

air)

High-powered thruster in a flexible, efficient, and light-weight package.

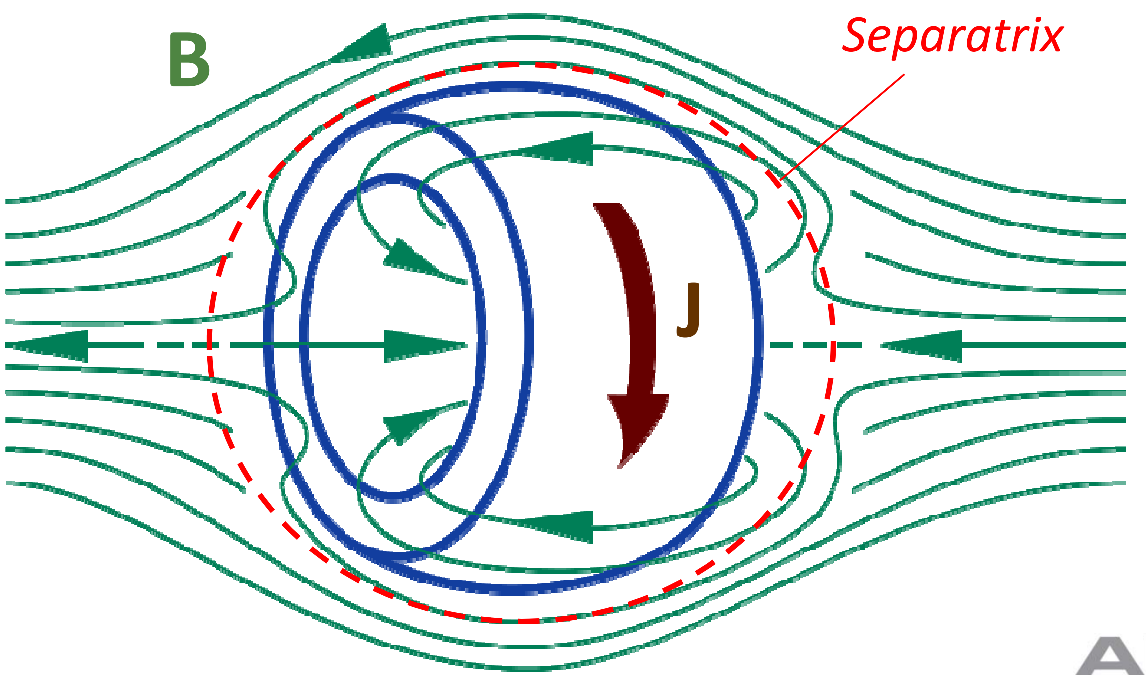
**projected*

[1] Brown, D., Beal, B., Haas, J. (2010) AFRL High Power Electric Propulsion Technology Development

What is an FRC?

An FRC is a plasma blob characterized by

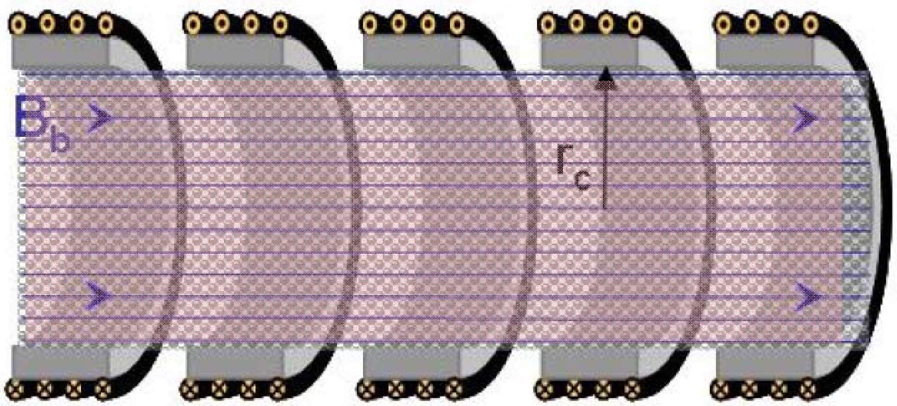
1. **Large azimuthal current (e^- or ions)**
2. **Closed magnetic surface**
3. **Reversed internal magnetic field**



Formation Stages

1. Preionization

Creates a uniform, low density plasma



[2] Slough, J. and Kirtley, D. (2009) Pulsed Plasmoid Propulsion – The ELF Thruster

Formation Stages

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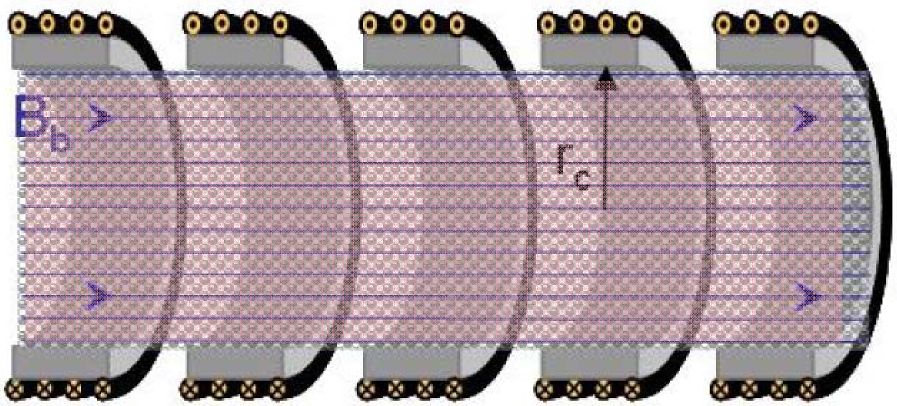
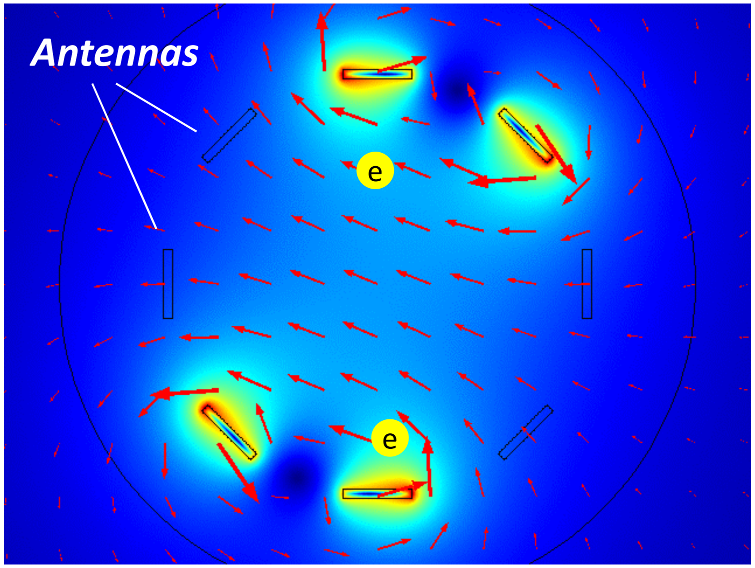


[2] Slough, J. and Kirtley, D. (2009) Pulsed Plasmoid Propulsion – The ELF Thruster

2. Rotating Magnetic Field

Electrons tied to rotating field lines → azimuthal current



Source: Nolan Uchizono

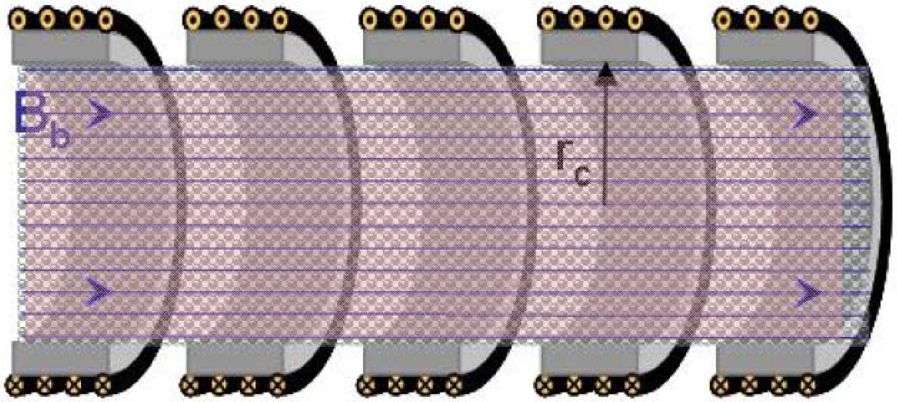
Condition: $\omega_{ci} < \omega_{RMF} < \omega_{ce}$

ω_c = cyclotron frequency

Formation Stages

1. Preionization

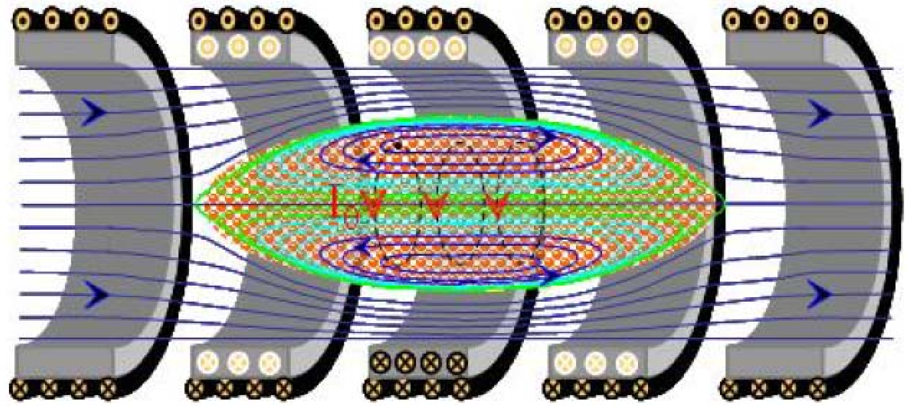
Creates a uniform, low density plasma



[2] Slough, J. and Kirtley, D. (2009) Pulsed Plasmoid Propulsion – The ELF Thruster

2. Rotating Magnetic Field

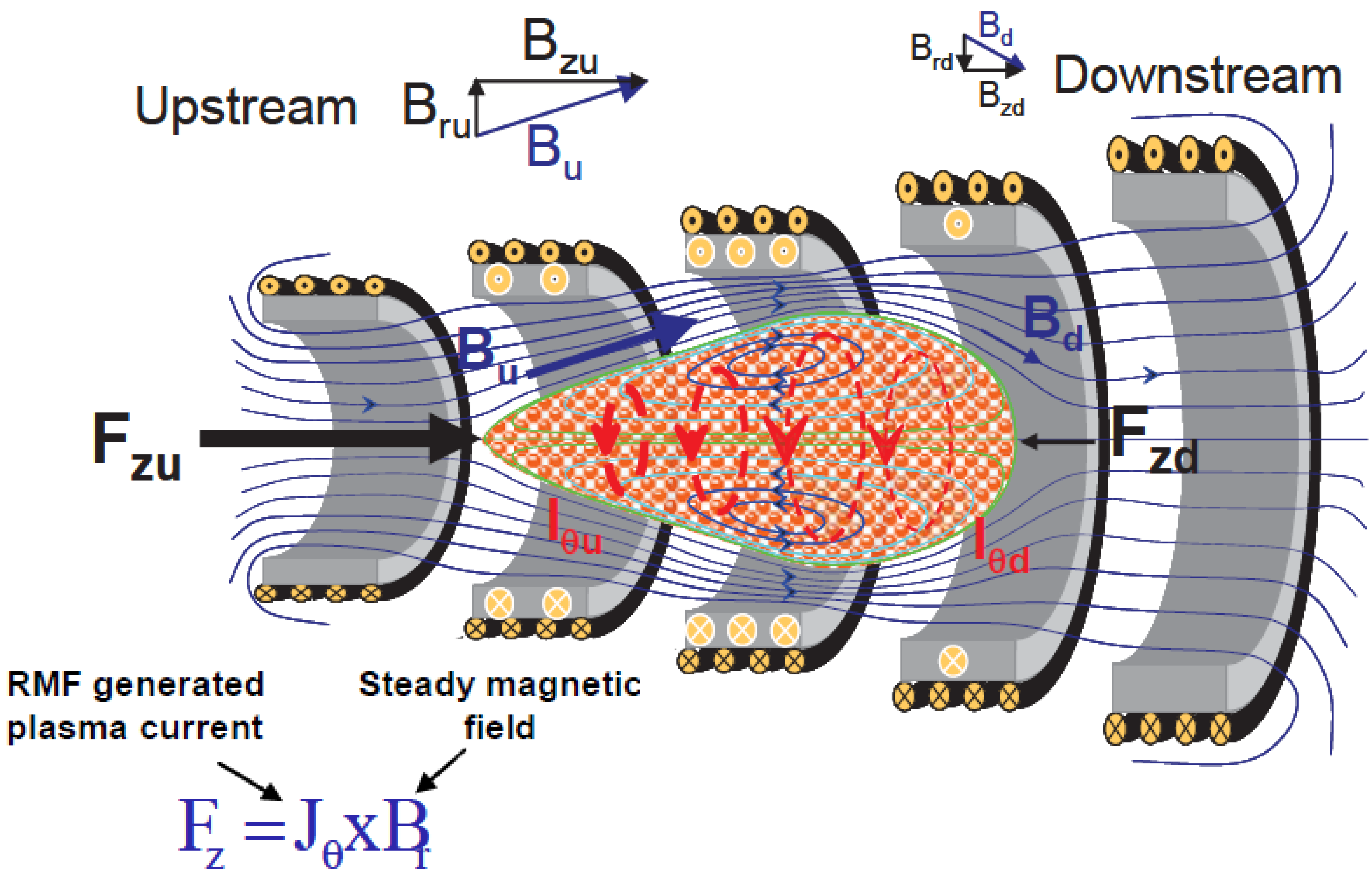
Azimuthal current reverses internal magnetic field



Magnetic field lines reconnect and form closed-surface FRC

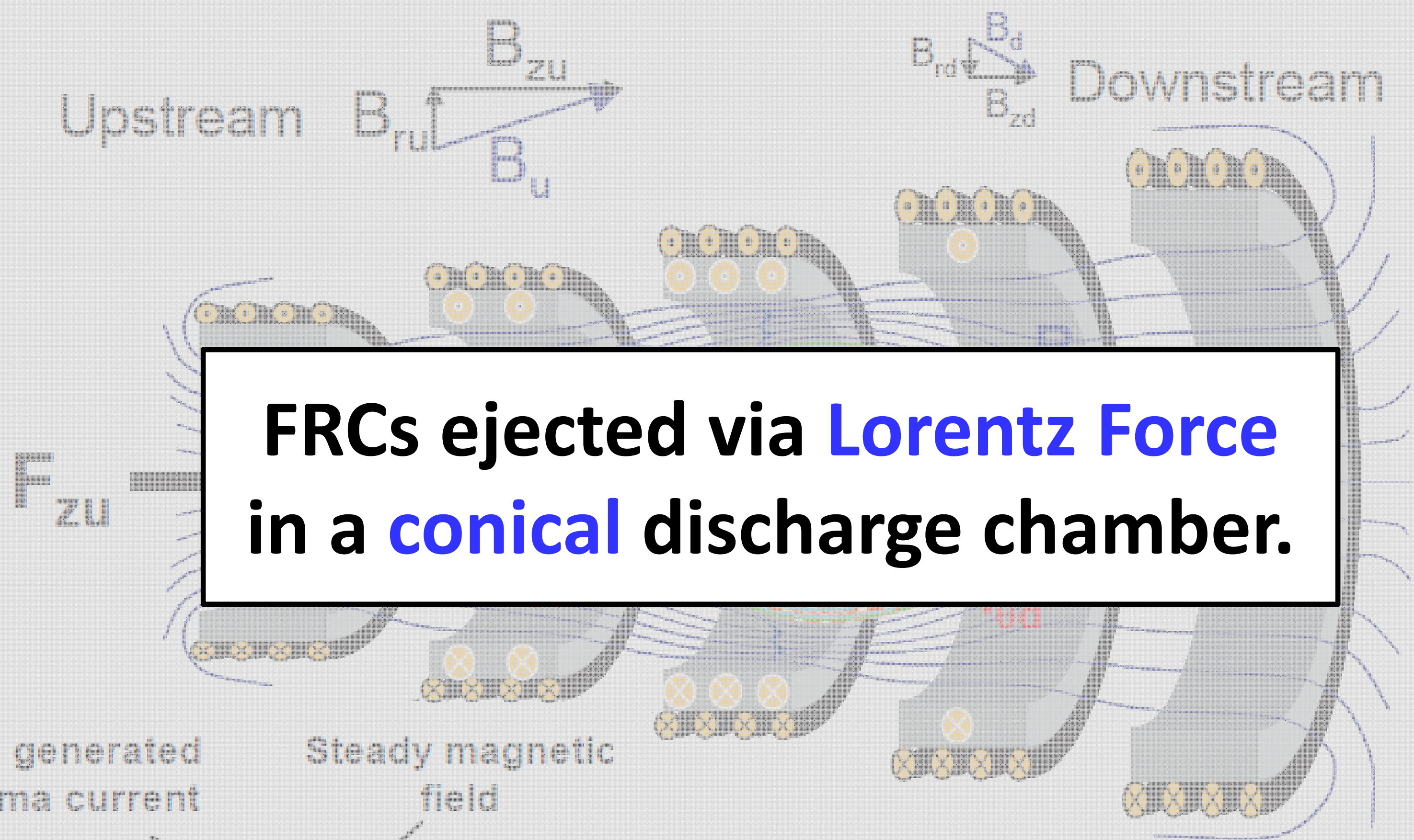
ω_c = cyclotron frequency

Translation



[3] Kirtley, D. et al. (2011) Steady Operation of an Electromagnetic Plasmoid Thruster

Translation



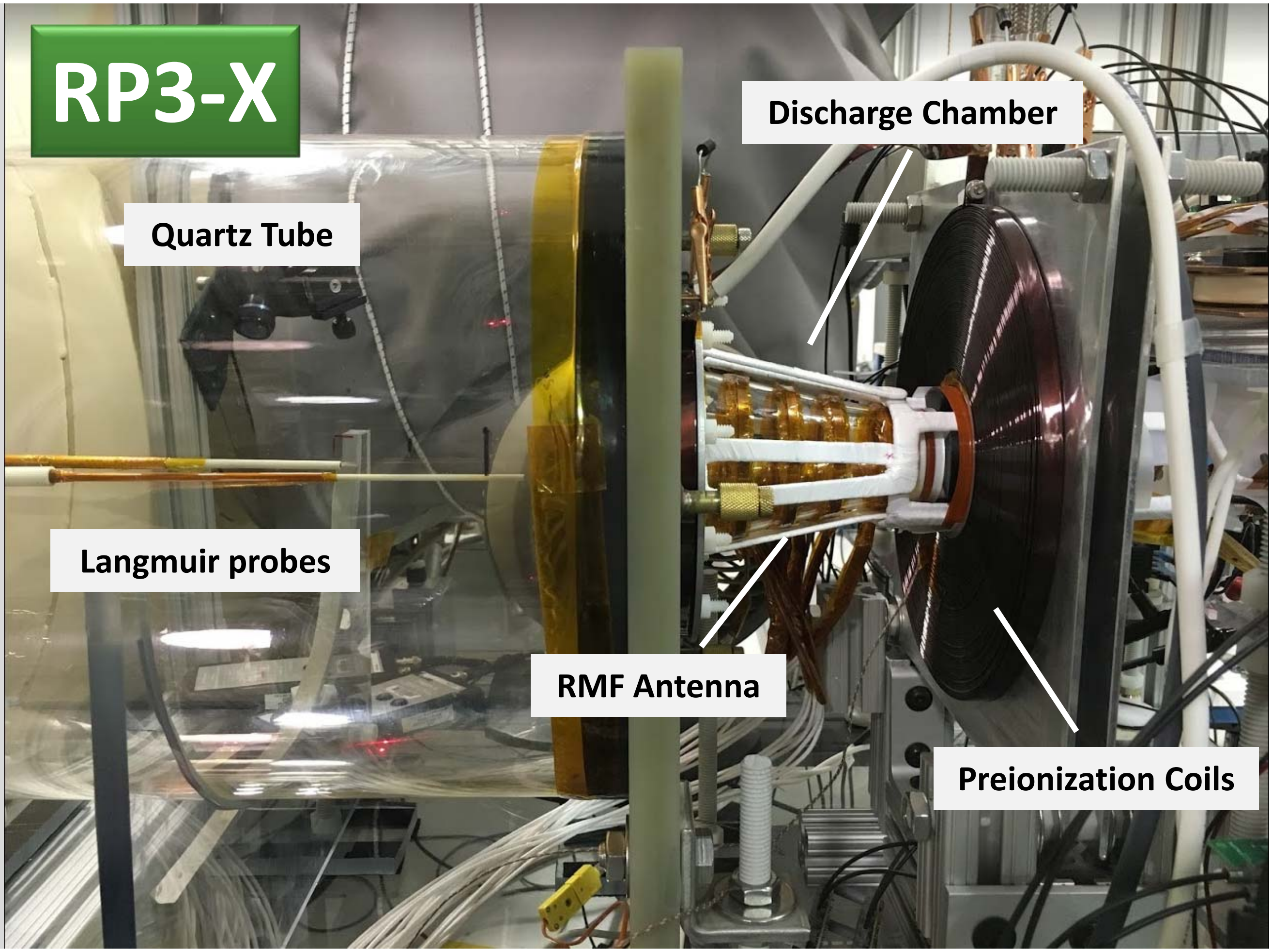
FRCs ejected via Lorentz Force in a conical discharge chamber.

$$F_z = J_\theta x B_r$$

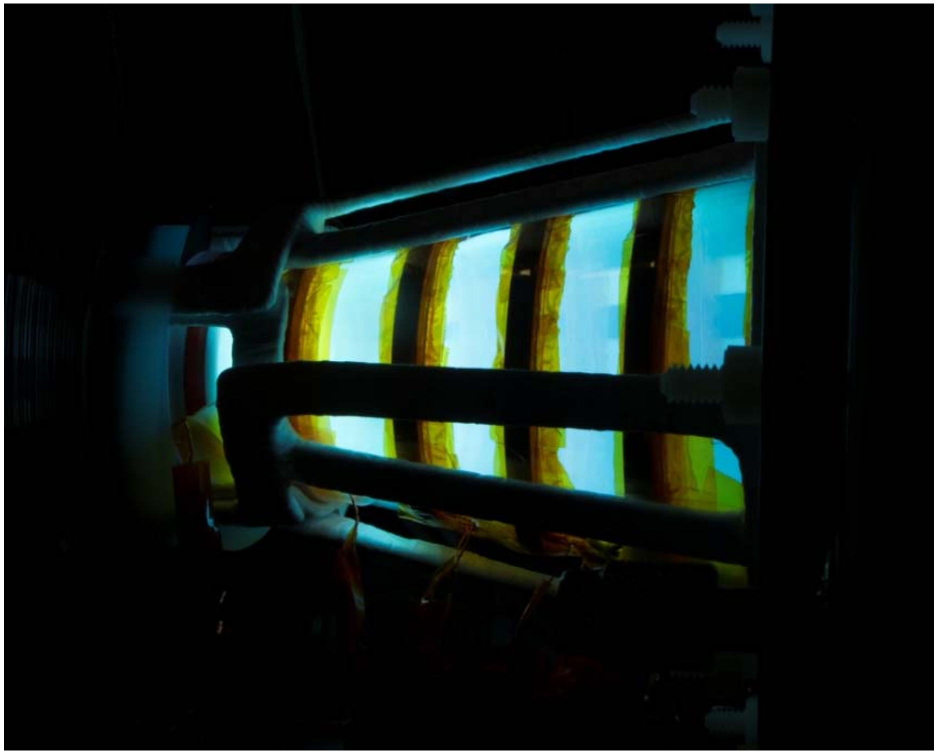
[3] Kirtley, D. et al. (2011) Steady Operation of an Electromagnetic Plasmoid Thruster

Experimental Setup

Chamber 3



RP3-X Operation



Source: Mike Holmes

FRC Settings

Flow Rate: 40 sccm

Operating Gas: xenon

Working Pressure: 4.6×10^{-5} Torr

FRC Energy (per pulse): 5 J

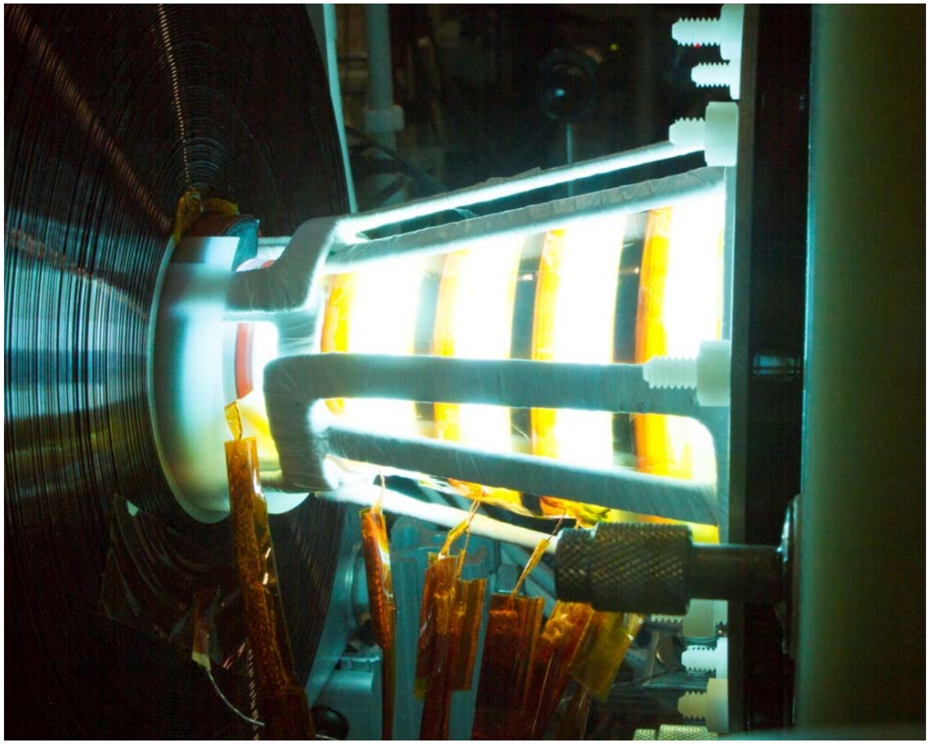
Pulse Frequency: 10 kHz

Time Delay btwn PI & RMF: 10 μs

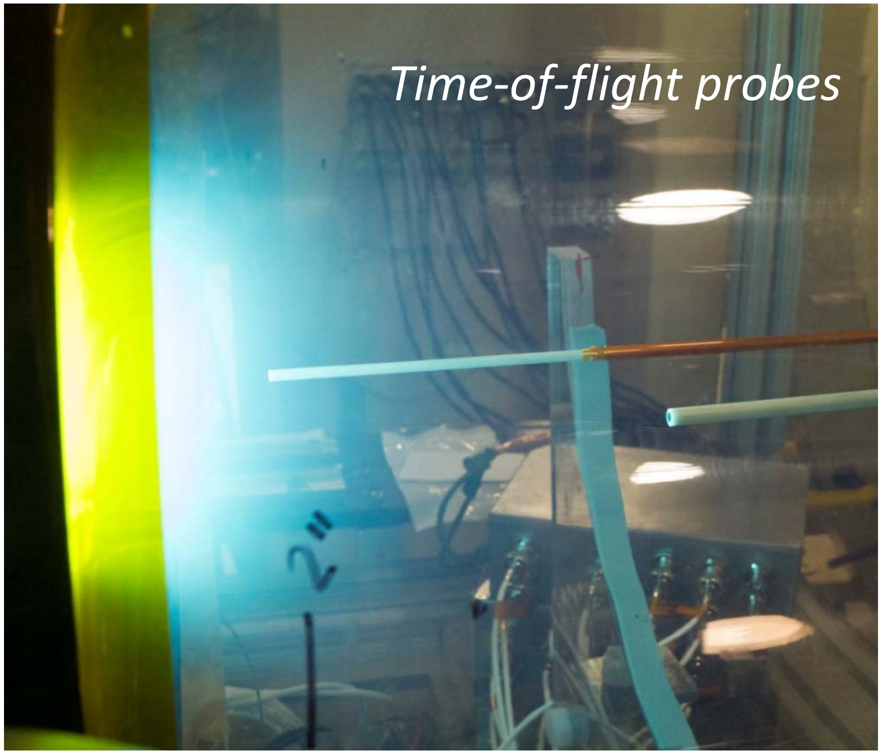
RMF Phase Delay: -5°

Bias Magnetic Field: 300 G

RP3-X Operation

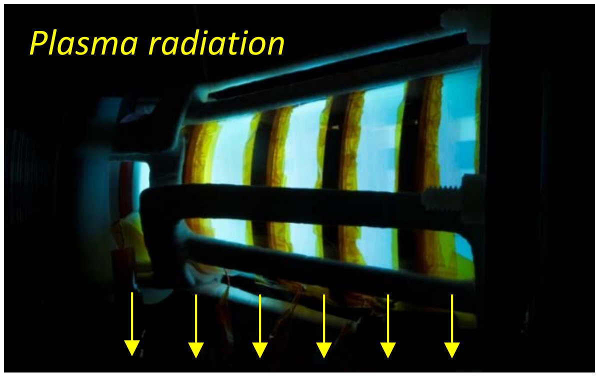


Source: Mike Holmes



Source: Mike Holmes

Optical Emission Spectroscopy (OES)



Collection Optics
to 600um fiber

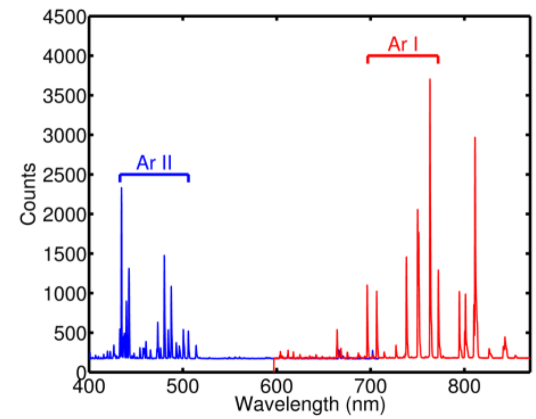
Spectrometer
(iHR 320)

Ion Streak Camera
(Hamamatsu C7700)

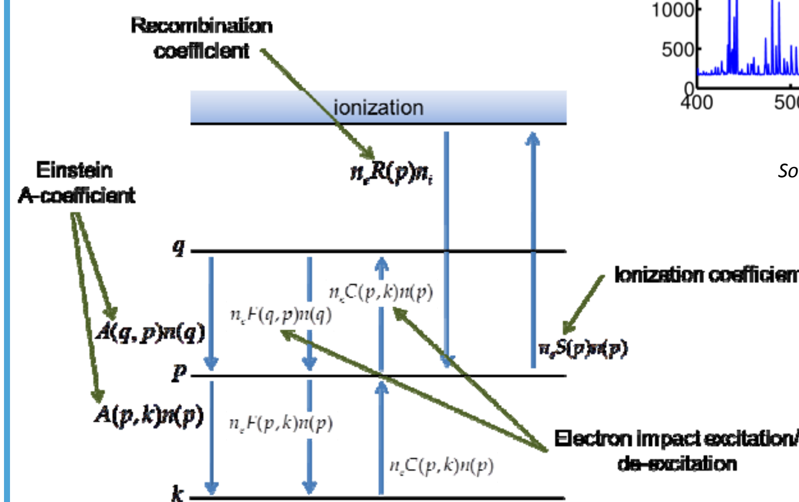
CCD Camera
(C10600)

Time-resolved OES allows for non-invasive measurements of plasma properties (n_e, T_e) in time.

1. Acquire Spectrum



Source: Scharer Research Group

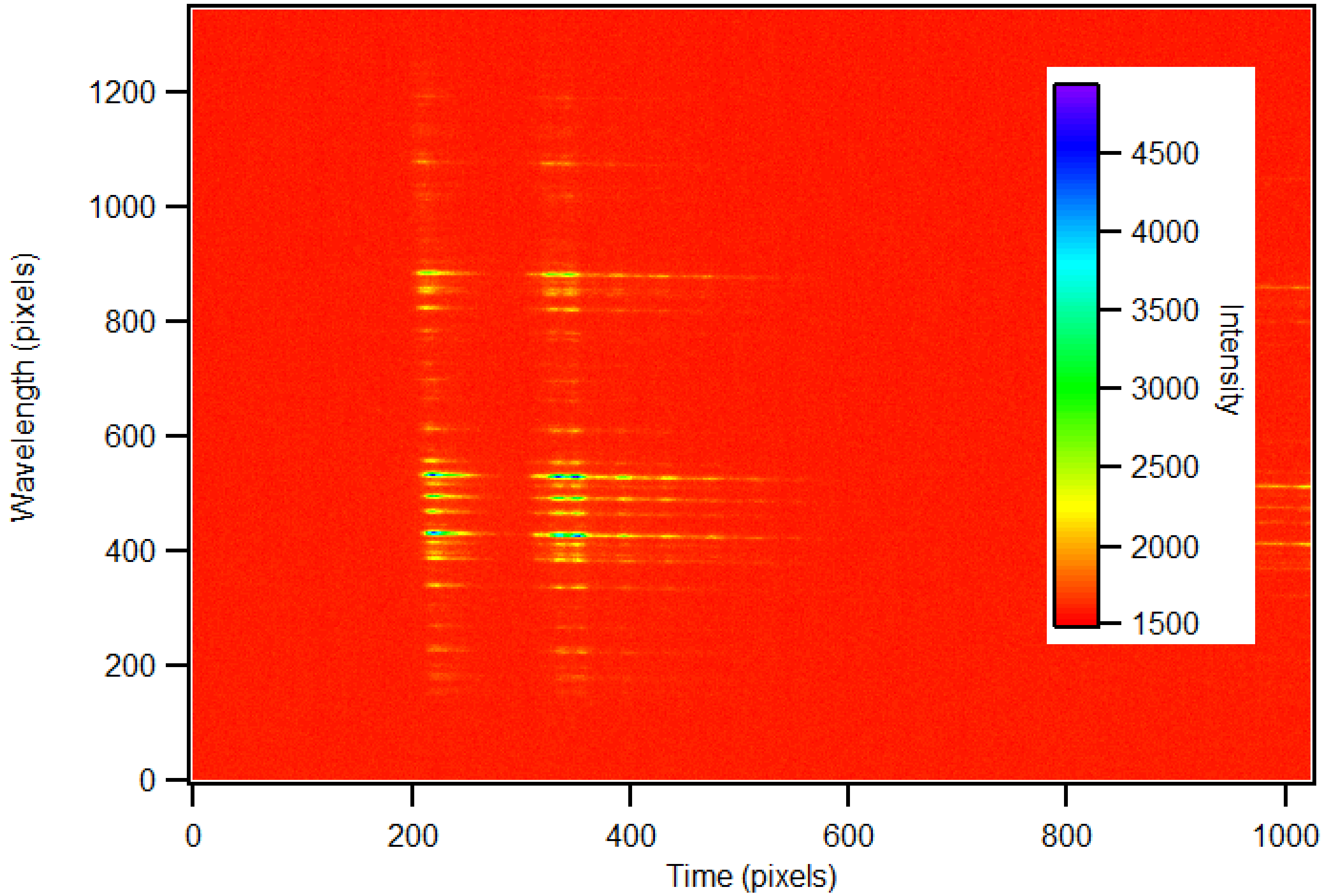


Source: PEARL

2. Compare to Collisional-Radiative Model (CRM)

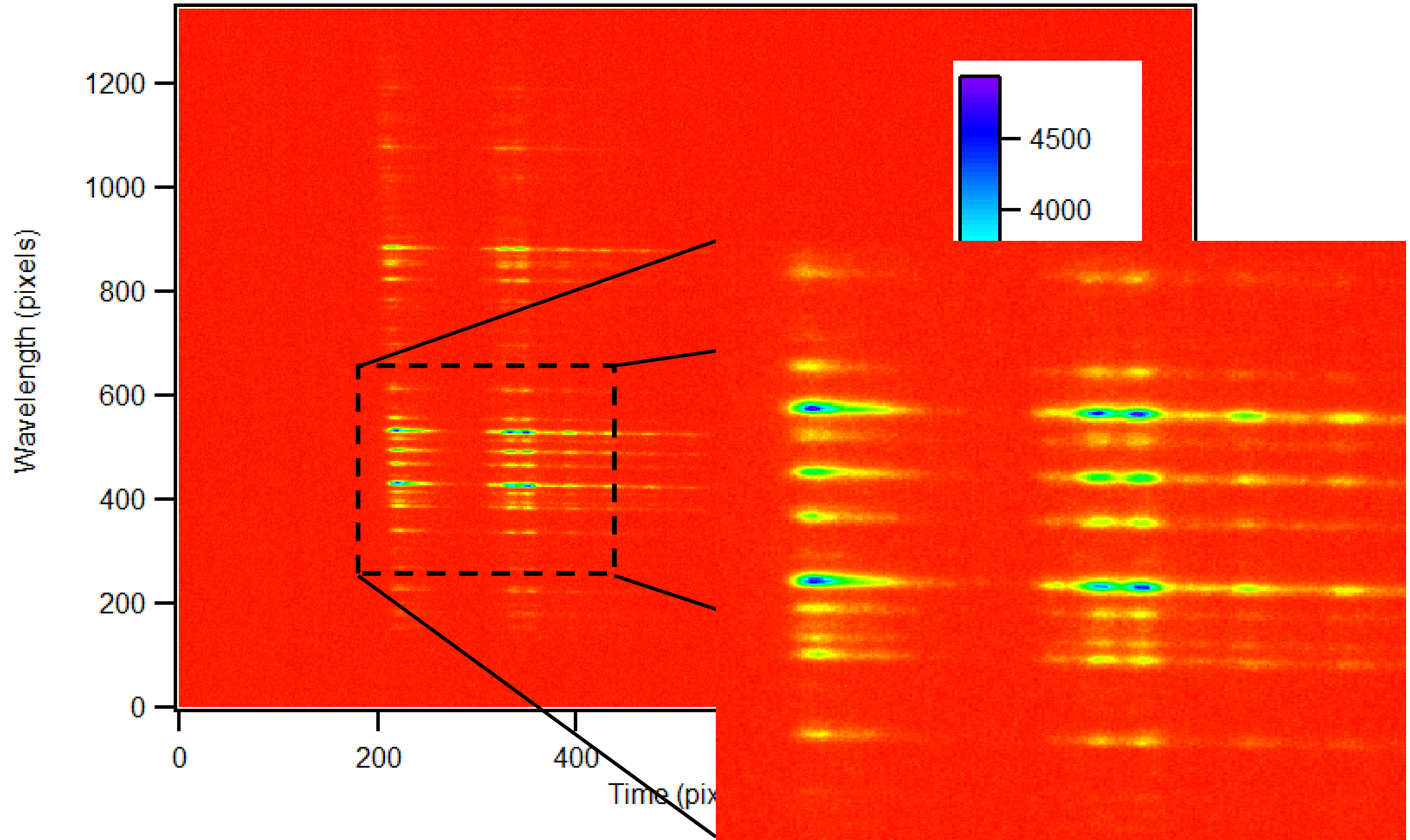
Data Processing

Raw Data



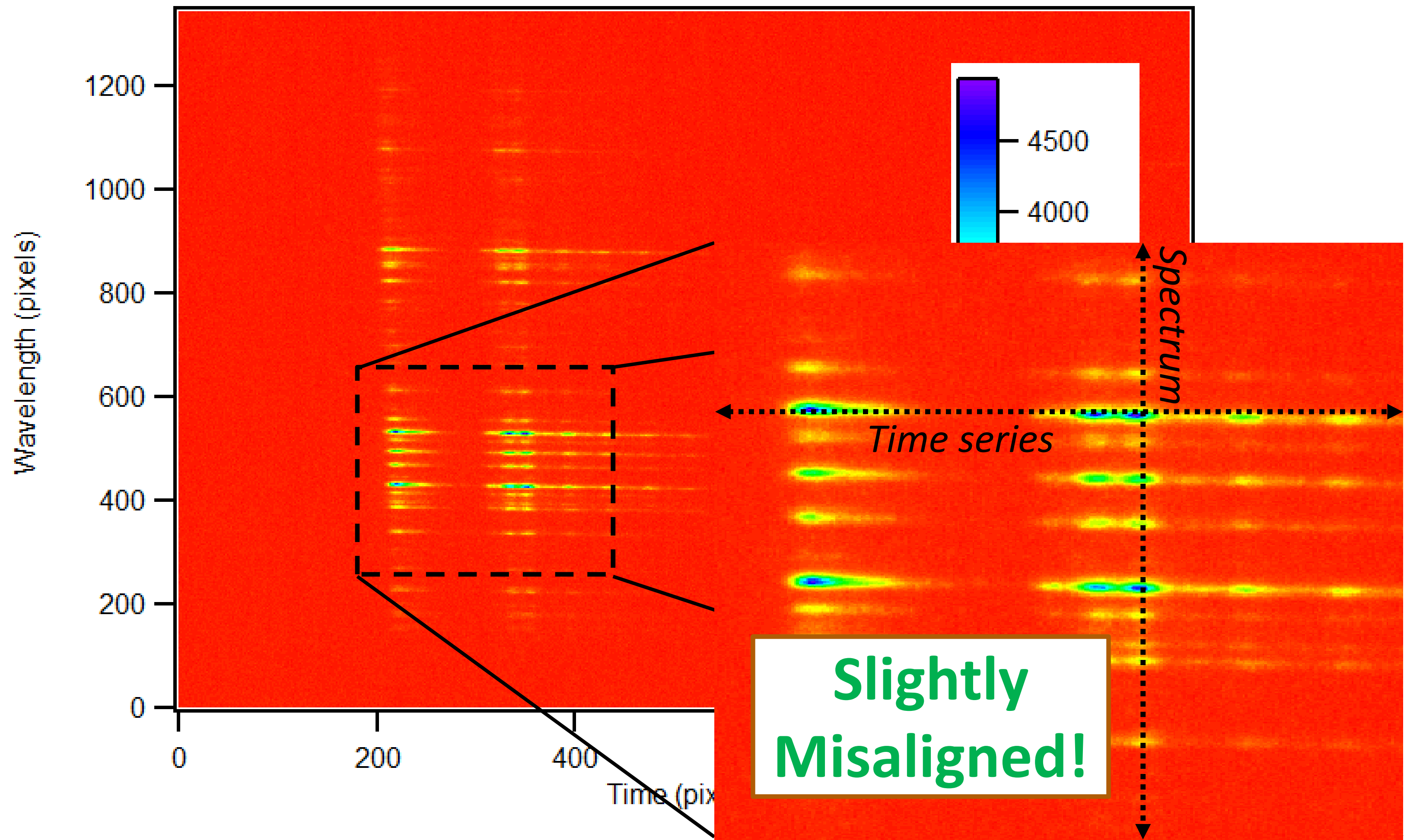
Data Processing

Raw Data



Data Processing

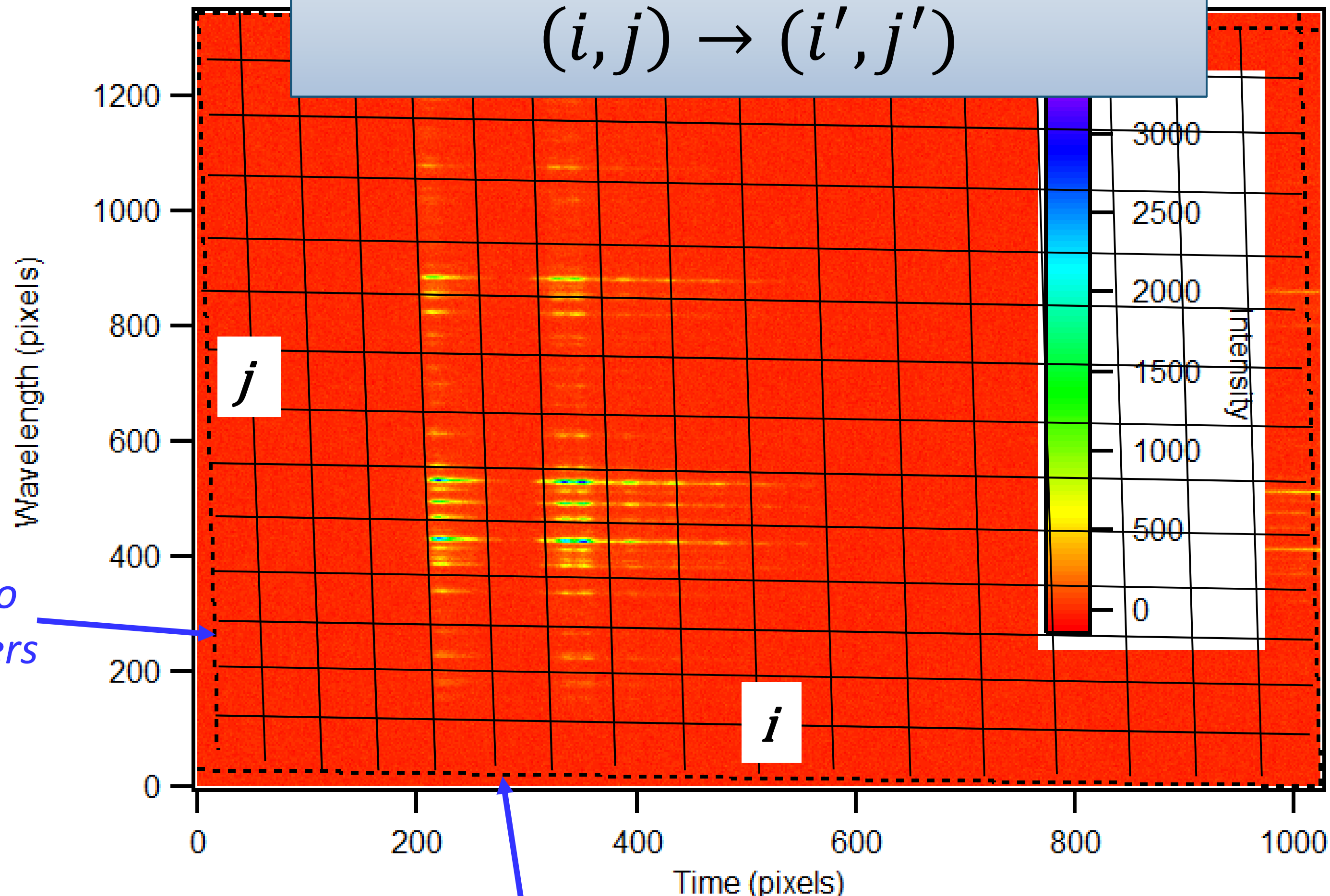
Raw Data



GL1

Data Processing

Mapping structured grid
$(i, j) \rightarrow (i', j')$

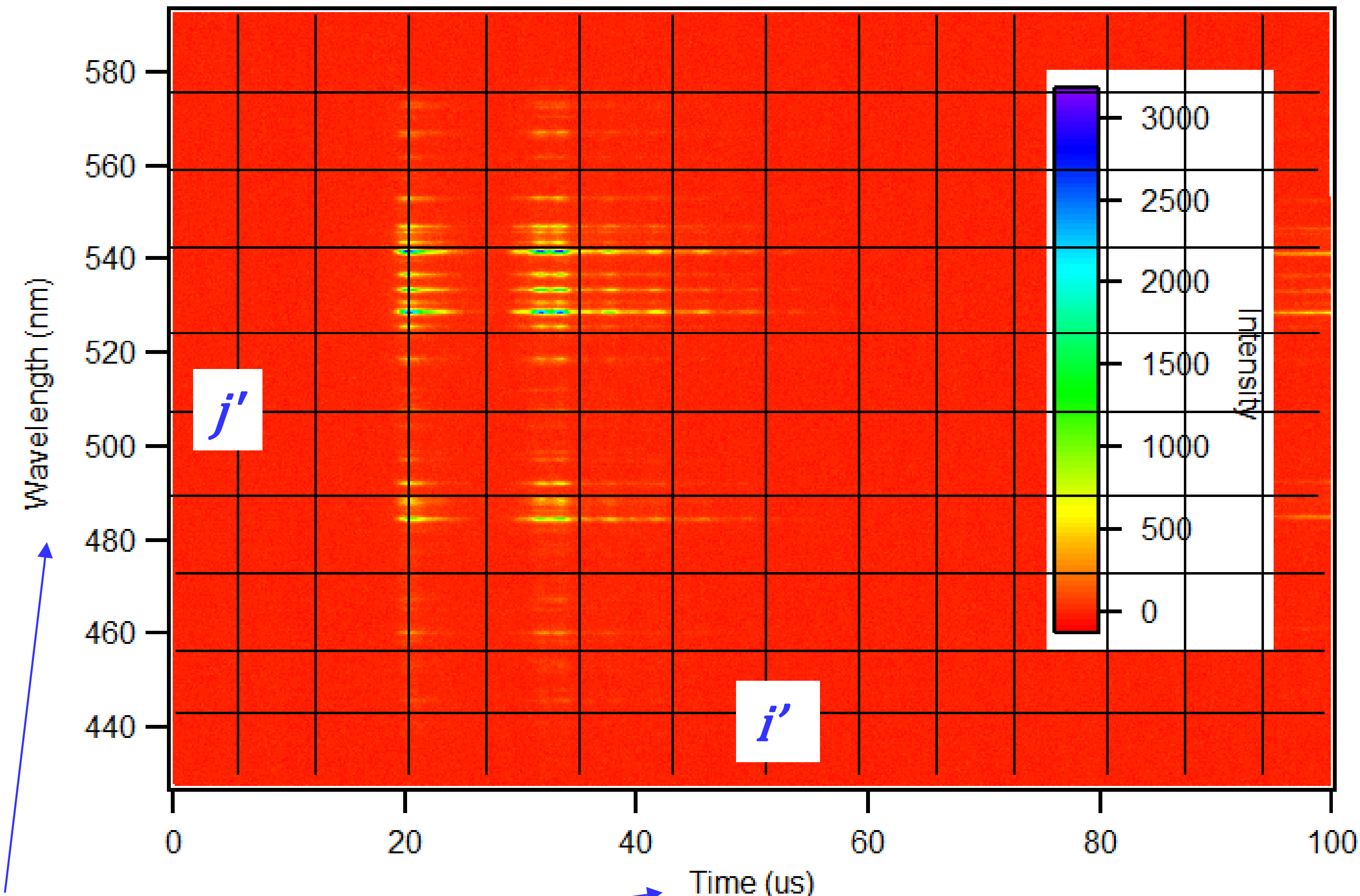


Linear fit to peak centers

Linear fit to streak lines

Data Processing

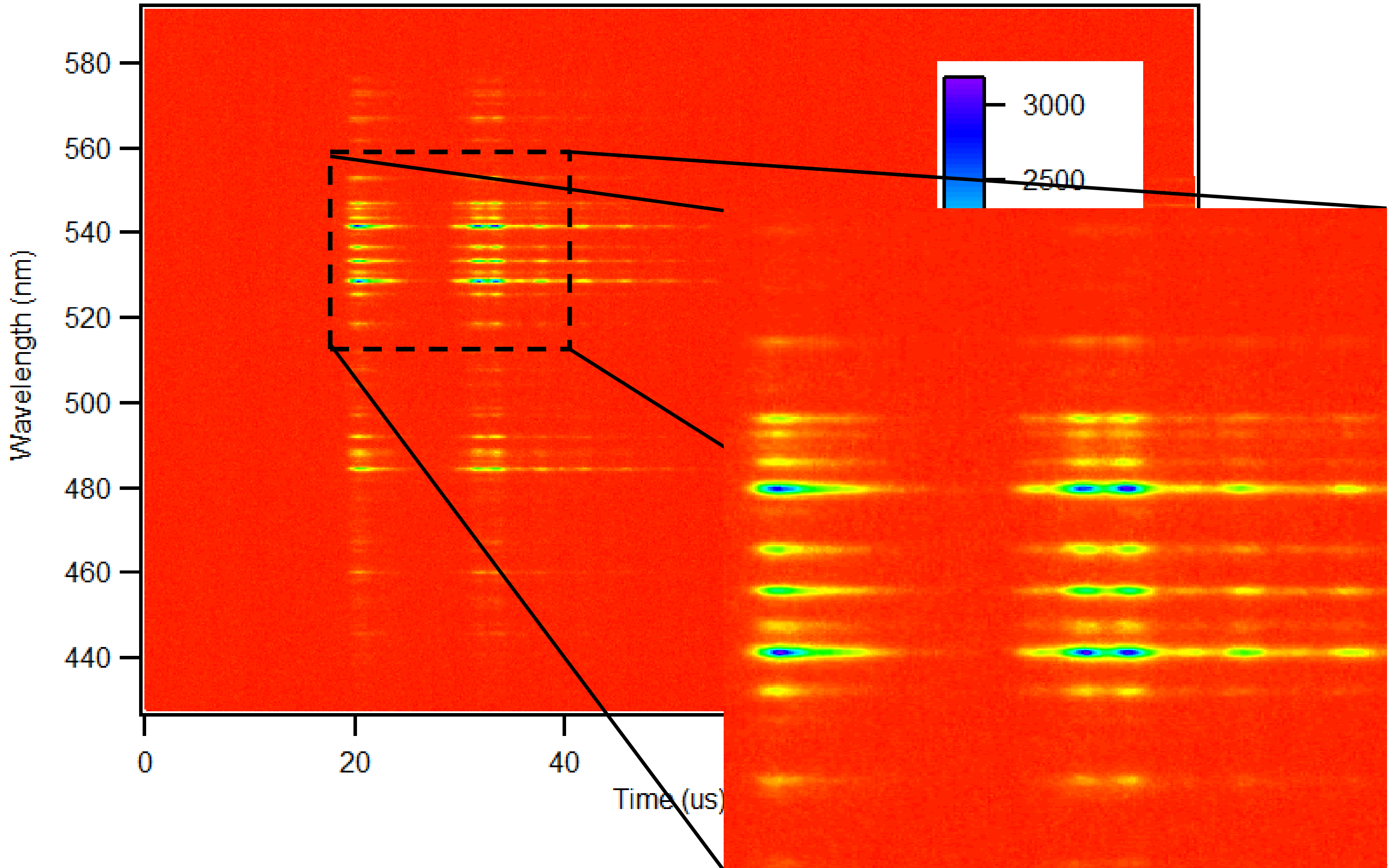
Corrected Data



Calibrated axes

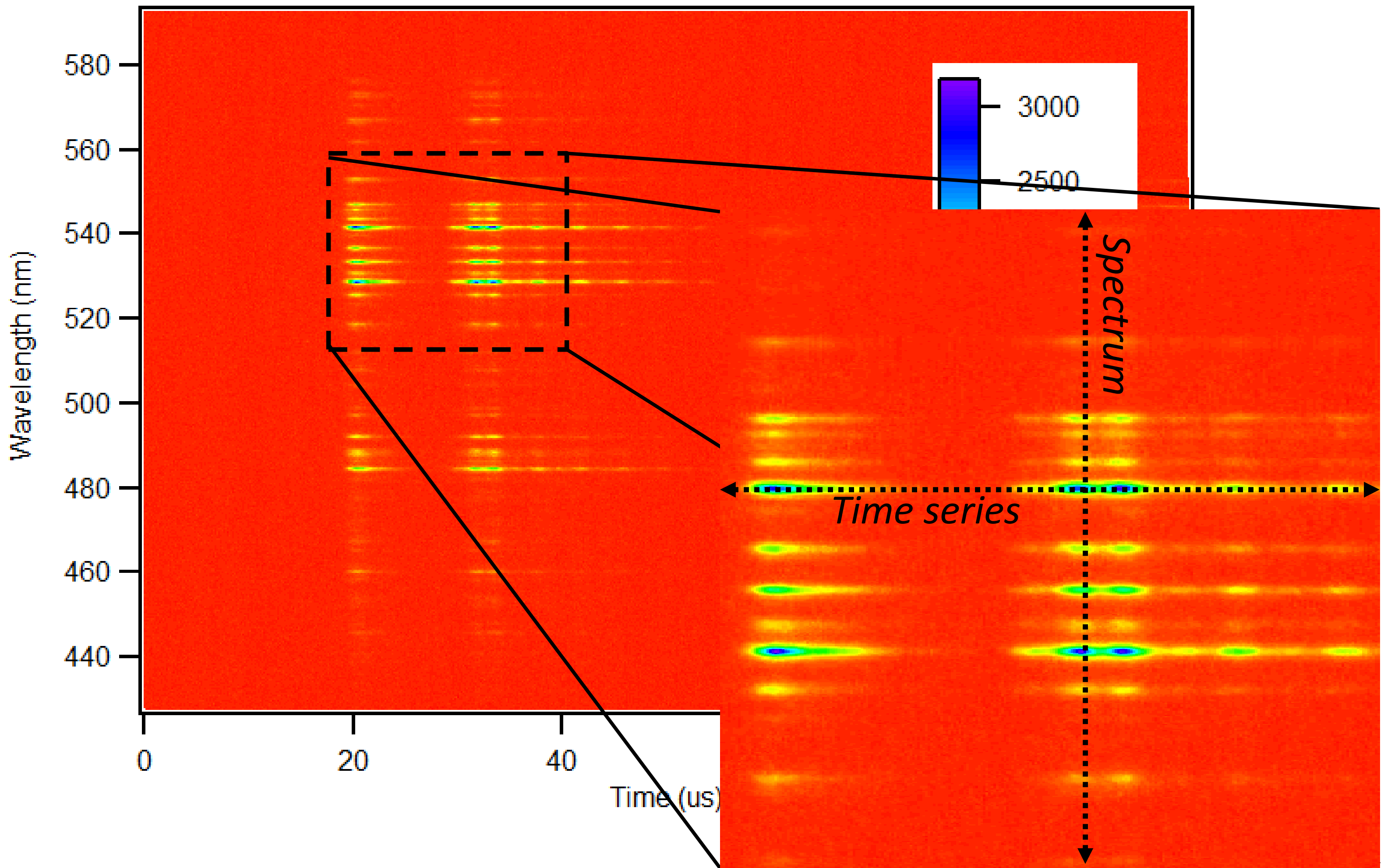
Data Processing

Corrected Data



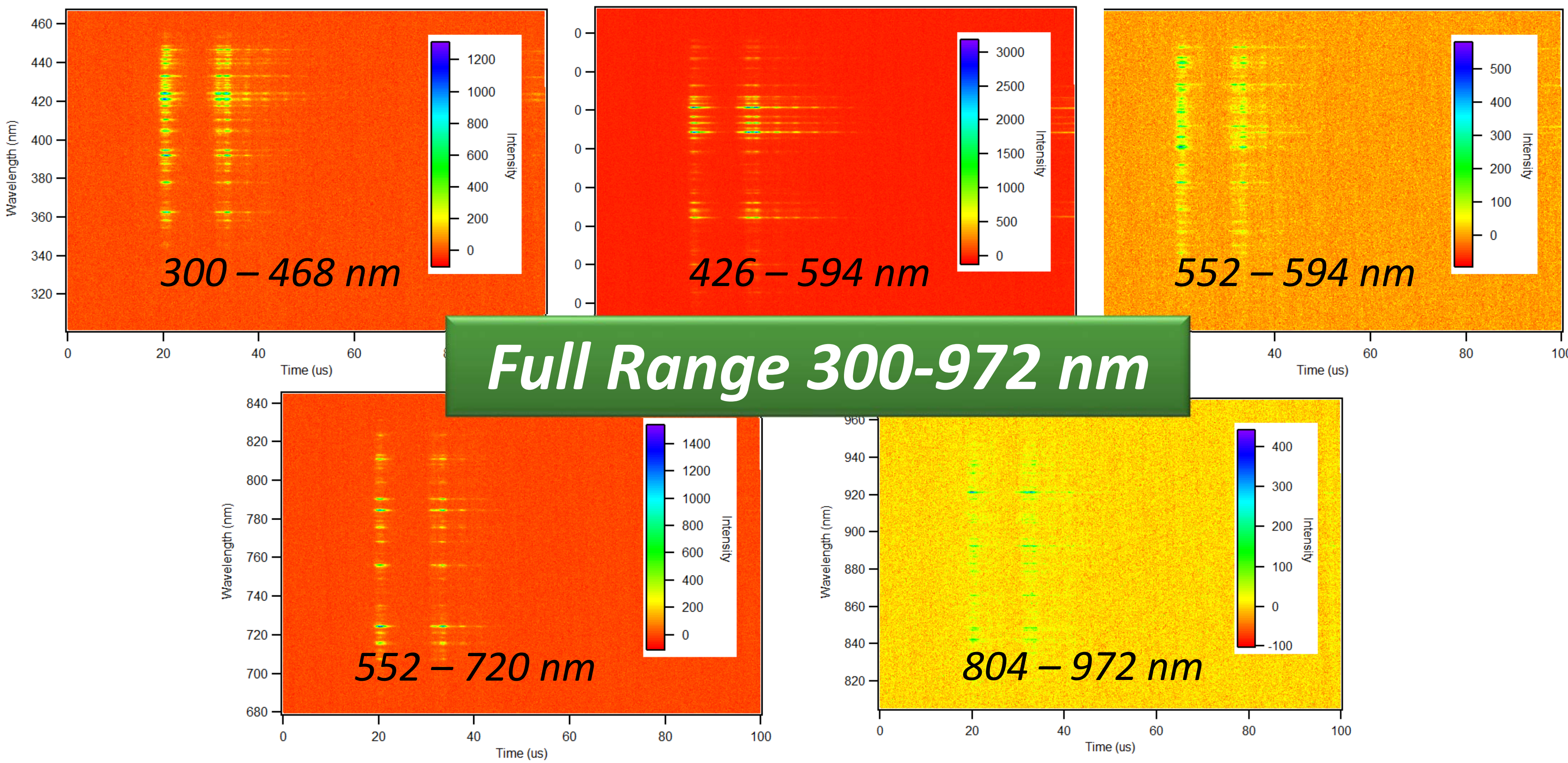
Data Processing

Corrected Data

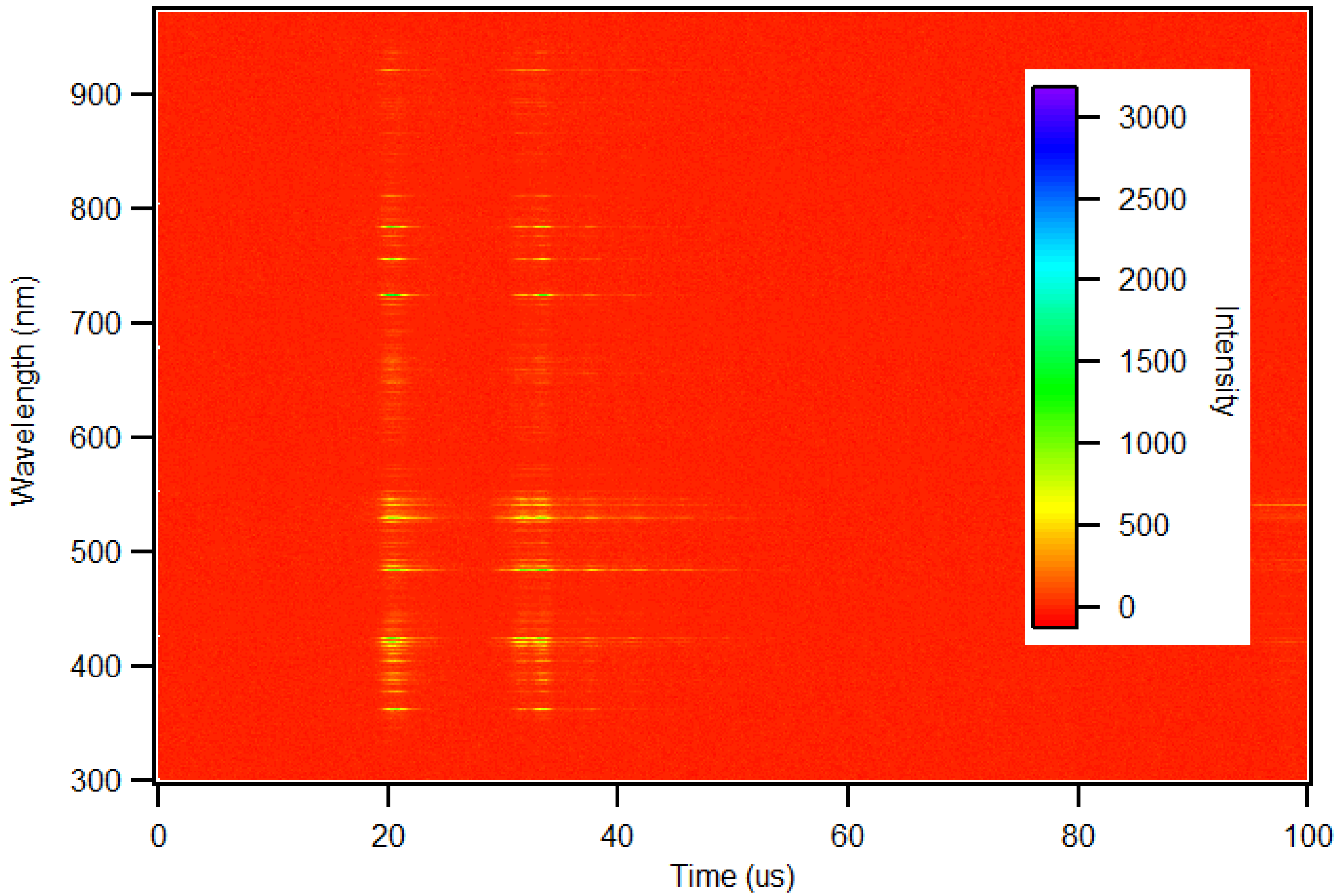


Data Processing

Mosaicking



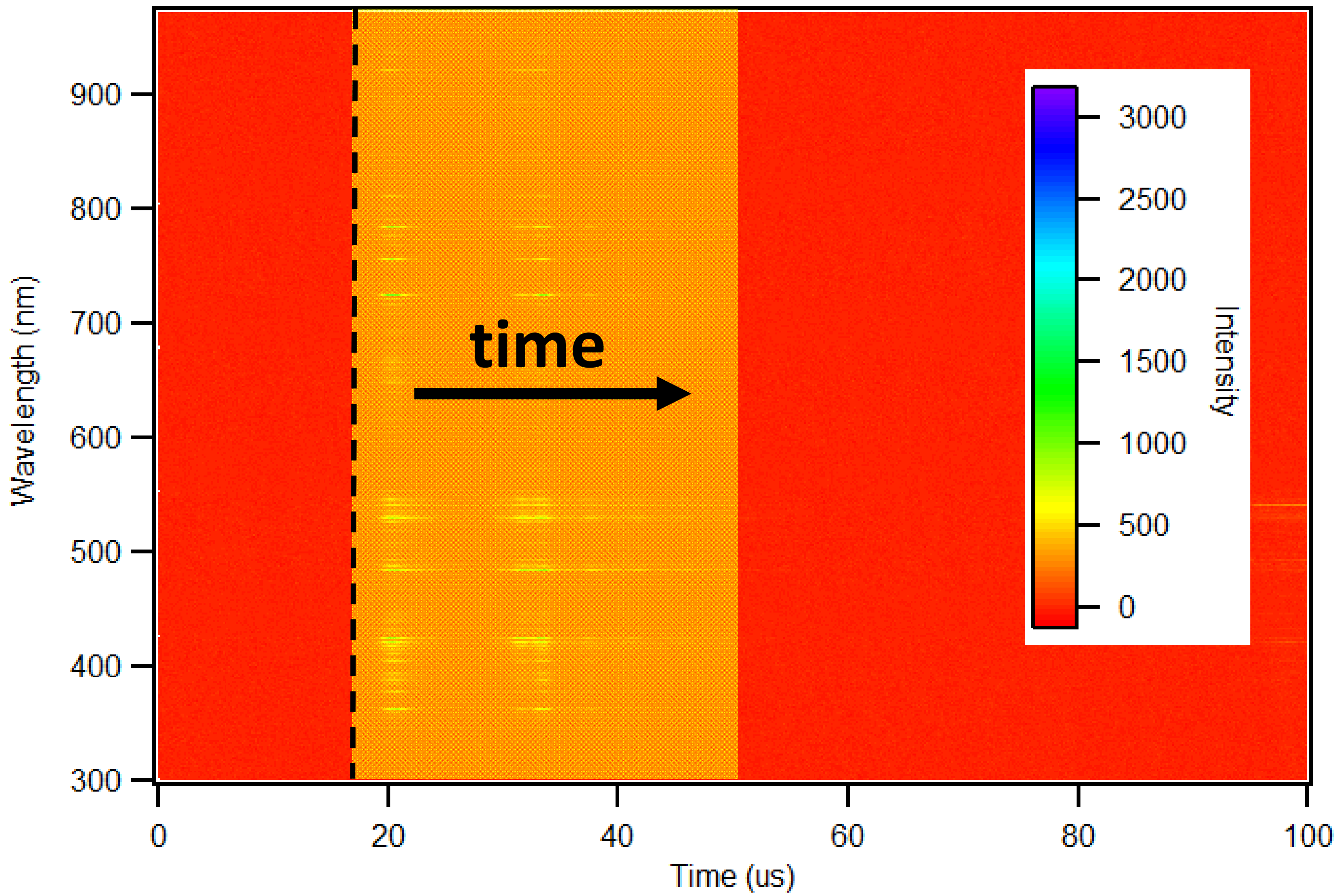
Results



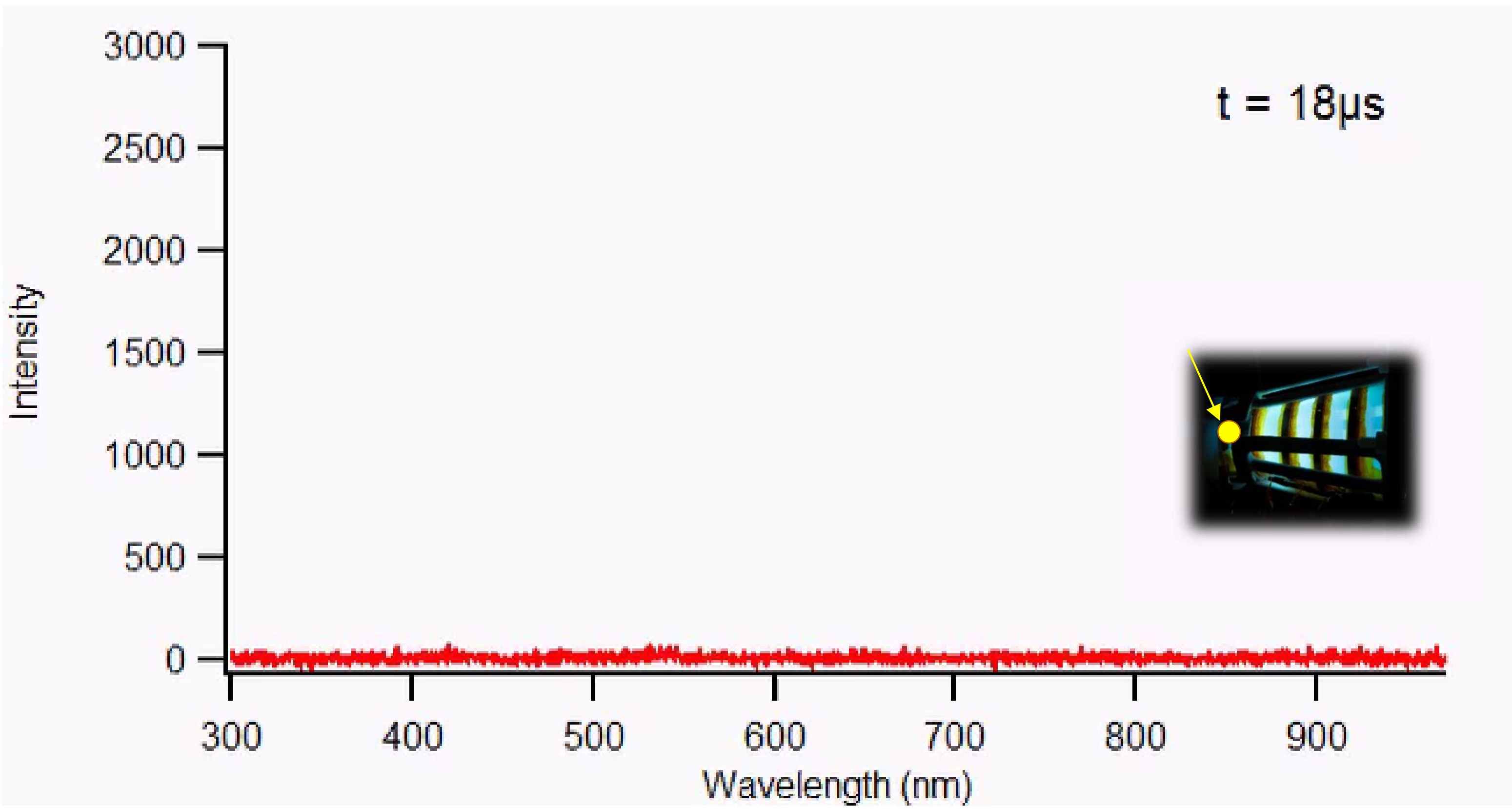
Wavelength (nm)
900
800
700
600
500
400
300
0
20
40
60
80
100
Time (us)
3000
2500
2000
1500
1000
500
0
Intensity

Results

Vertical slice = spectrum at time t



Results



t = 18μs
Intensity
3000
2500
2000
1500
1000
500
0
300
400
500
600
700
800
900
Wavelength (nm)

Results

Time-resolved OES will allow us to answer the following questions:

Is the preionization efficient?

How much gas is ionized?

How hot is the plasma?

How dense is the plasma?

Conclusions

- Designed and setup collection optics

- Established data processing pipeline

- Demonstrated capability of streak camera to capture time-dependent FRC spectra

Future Work

- Line identification of xenon spectrum
- Perform intensity calibration (deuterium lamp)
- Obtain Argon FRC data and use Collisional Radiative Model (CRM) to extract plasma properties
- Apply knowledge to improve FRC thruster design

Acknowledgments

- Carrie Hill
- Mike Holmes
- Nolan Uchizono
- ERC
- Cece’s Cuisine

Backup Slides

Data Analysis

Background Subtraction